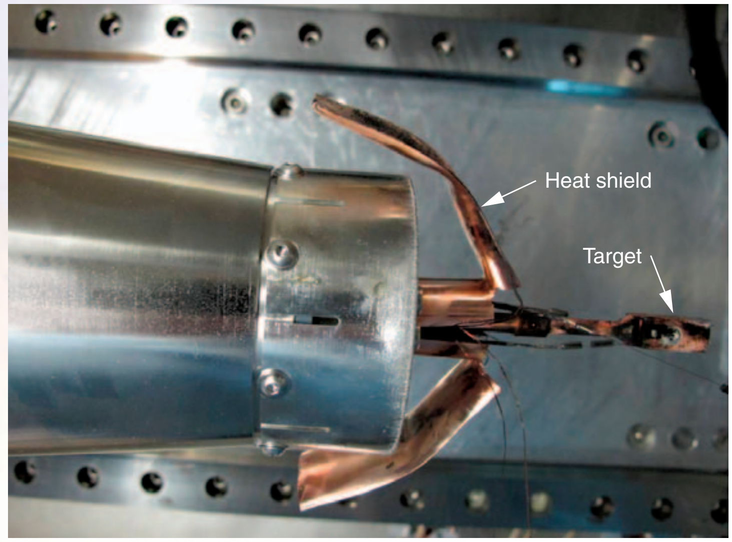
Targets Designed for Ignition



A postshot photograph of a bent heat shield surrounding a spent target illustrates the energy concentrated on the target during a hohlraum energetics experiment at the National Ignition Facility (NIF).

AS the world's population continues to grow at a brisk pace, more and more people aspire to the lifestyle and energy consumption levels of industrialized countries. The world's energy needs are increasing rapidly, but supplies of the most convenient forms of fuel are finite. Commercial fusion power has the potential to fill the gap between supply and demand by providing an affordable, virtually limitless source of energy. But first, the technology must pass an important test: demonstrating that self-sustaining fusion reactions can be achieved and reproduced in the laboratory.

Research teams worldwide have been working on this science and engineering grand challenge for decades. Experiments at the National Ignition Facility (NIF), the world's largest, most energetic laser, are the next major step toward making fusion a viable energy source. In 2009, a multidisciplinary team of scientists from Lawrence Livermore and its partners on the National Ignition Campaign (NIC)—Los Alamos and Sandia national laboratories, the Laboratory for Laser Energetics at the University of Rochester, General Atomics, Massachusetts Institute of Technology, Commissariat à l'Énergie Atomique in France, and Atomic Weapons Establishment in the United Kingdom—conducted a series of NIF experiments to validate and optimize the target design for upcoming ignition experiments. These hohlraum energetics shots, together with laser commissioning (see *S&TR*, April/May 2010, pp. 4–11) and fueling targets with tritium, are the final pieces needed to demonstrate that the giant laser is ready for the first credible ignition experiments.

NIF experiments are designed to achieve ignition through indirect-drive, inertial-confinement fusion. Rather than directing laser beams to hit a target for direct-drive ignition, NIF's 192 beams are focused through a hole in the top and bottom of a gas-filled, gold hohlraum—a centimeter-size enclosure that traps radiation. In the center of the hohlraum is a 2-millimeter-diameter pellet filled with nuclear fuel in both gas and solid forms. (See *S&TR*, July/August 2007, pp. 12–19.) During a shot, laser beams strike the internal walls of the cryogenically cooled hohlraum and are converted to x rays that irradiate and heat the outer layer of the fuel pellet. As this layer expands and ablates, it rapidly compresses the pellet's core, driving it to temperatures and pressures greater than those in the interior of the Sun. These extreme conditions cause the fuel's nuclei to fuse and release far more energy than was necessary to initiate the reaction.

The NIC team divided the hohlraum shot series, a precursor to ignition attempts, into three sets that progressively scale up the complexity, laser power, and hohlraum size of experiments. In the first set, researchers activated 20 major optical, x-ray, and neutron diagnostic instruments, which together provide more than 200 streams of data for every experiment. The goal for the first sequence was to assess diagnostic performance, so the hohlraums in these 24 shots were either empty or filled with gas and kept at room temperature.

Once the diagnostics were brought on-line, the experimenters could gather data in subsequent shots to determine whether the hohlraum produces the environment needed for ignition. The second shot sequence focused on cryogenics and the third on hohlraum energetics. These 45 shots used hohlraums cooled to –253°C, similar to the anticipated ignition targets but with dummy capsules. In the cryogenics series, researchers assessed whether the hohlraum could be kept at the optimum temperature for fuel capsule performance and whether mechanical components associated with target cooling would cause undesirable laser light reflections. The energetics sequence examined the x-ray environment within the hohlraum to ensure that each shot would achieve the required temperature and symmetry.

Even Small Targets Provide Grand Data

The first experiments in the energetics series were conducted with scaled-down targets and laser energies ranging from 500 to 800 kilojoules, lower than researchers expect to use for ignition. The series culminated in a 1-megajoule shot on a full-scale, 1-centimeter-long hohlraum. After analyzing results from these shots, the NIC team now predicts that 1.2 to 1.3 megajoules of energy must be delivered to the target for successful fusion experiments. According to Livermore physicist Siegfried Glenzer, conducting the early portion of the campaign with lower energies and smaller targets was prudent. By scaling the energy and hohlraum size, researchers can obtain important information on hohlraum physics and make relevant measurements while minimizing risk.

"We want to be good stewards and not damage the facility if something unexpected happened," says Glenzer, who led the energetics experiments. "Our team worked hard to make the most of these experiments. The quality of each shot was outstanding, and we tried to learn the maximum amount on every one. The results gave us confidence that we're making strides toward getting the right hohlraum with the right performance for ignition."

Limiting Escaped Light

One uncertainty that the NIC team set out to resolve is whether laser–plasma interactions in the hohlraum would sap enough energy to thwart pellet fuel compression. These interactions could cause laser light to scatter away from the hohlraum, a process that is difficult to model and thus predict accurately.

"Backscatter can reflect a substantial amount of laser light, which reduces the energy that is coupled to the target in the first place," says Glenzer. "It can also accelerate electrons in a plasma, causing the capsule to preheat and making it harder to compress." A gas of charged particles, plasma is an inevitable result of the extreme temperatures and pressures within the hohlraum. However, if the plasma redirects valuable energy away from the fuel pellet, it interferes with the creation of the uniform x-ray field needed to evenly compress the target.

Livermore's Nathan Meezan, lead target designer for the energetics shot series, says, "Laser–plasma interactions were a major consideration when designing the experiments." And the results yielded surprising information about backscatter. In room-temperature shots on hohlraums filled with pentane gas—control shots, of a sort—very little backscatter occurred. The physicists then switched to a mixture of 80 percent helium and 20 percent hydrogen, two gases that do not freeze at cryogenic temperatures. Previous experiments with the OMEGA laser at the Laboratory for Laser Energetics indicated that this mixture would dampen a type of backscatter known as stimulated Brillouin scattering. But on the NIF shots, the helium–hydrogen combination produced significant Raman backscattering, an unexpected effect.

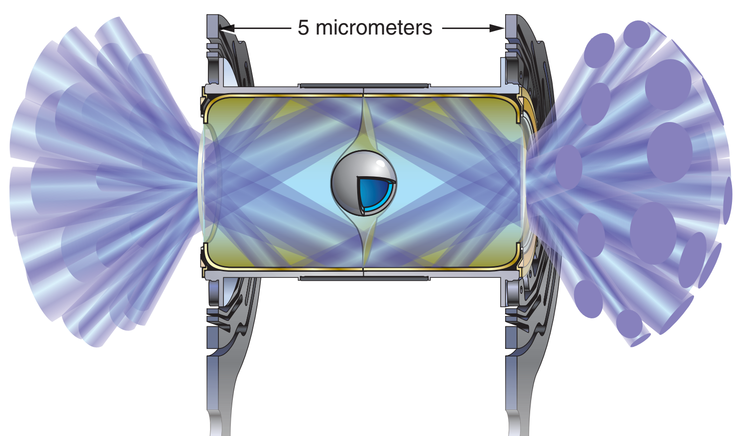
Calculations made by Livermore physicist Denise Hinkel showed that a pure helium gas fill would reduce Raman scattering. To test that prediction, the NIC team filled a fuel capsule with 100 percent helium but made no other changes to the target. The Raman backscatter decreased by more than a factor of two. Stimulated Brillouin scattering turned out to be of little concern for this target design. In fact, overall, the plasma did not cause as much interference as projected. On subsequent shots, less than 5 percent of energy was lost because of backscatter.

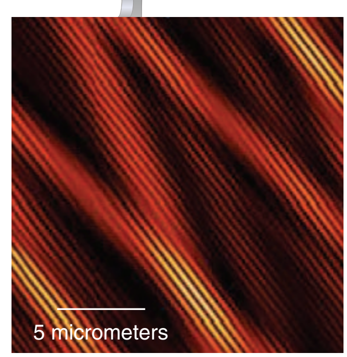
Results throughout the energetics shot series were even better than scientists had predicted. Data consistently agreed with previous computer models and calculations. Because of NIF's reliability and flexibility, the cryogenics experiments went smoothly. In earlier experiments with lasers such as OMEGA and Nova (the Laboratory's predecessor to NIF), obtaining consistent results and reliable data on this type of experiment was a challenge. With NIF, the cryogenic hohlraums heated almost as effectively as empty targets.

Another surprise finding was that simpler materials seemed to work as well as or better than combinations of materials. Just as helium proved to be a better hohlraum gas than the helium–hydrogen mixture, a hohlraum lined with gold performed as well as one with a more complex gold–boron lining. Because each NIF shot is such an elaborate enterprise, physicists welcome even minor reductions in complexity.

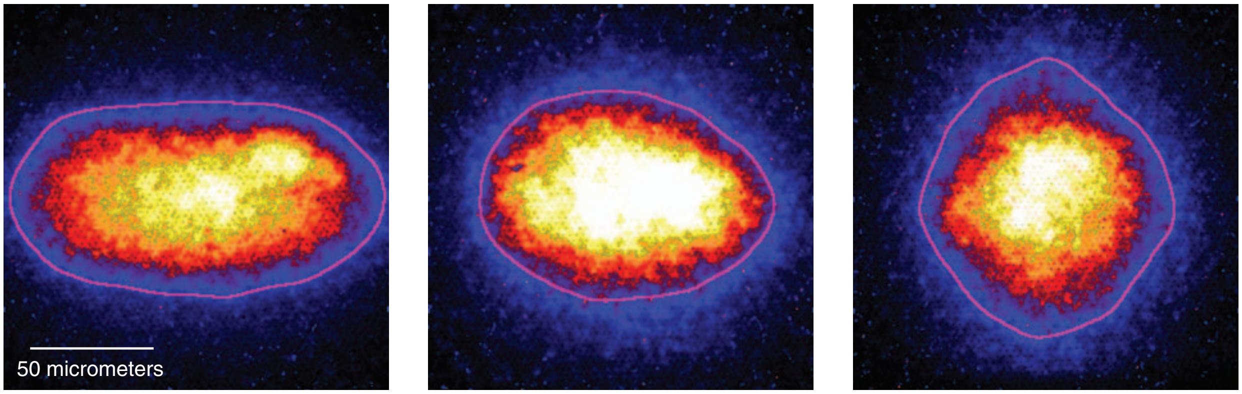
Tuning Beams to Balance Power

Implosion by nature is an unstable process. To improve the chances for success at creating fusion, scientists work diligently to make the conditions as precise and consistent as possible. For example, the fuel capsule must absorb energy in an even and controlled fashion to create a symmetric compression. With NIF, laser beams enter through holes in the top and bottom of the hohlraum and form two "cones." The outer cone shines laser





(above) In this cutaway drawing, NIF's 192 laser beams enter holes on both sides of the hohlraum and strike its inner walls, forming an x-ray field that heats the fuel capsule at the center. (right) Results from a NIF experiment show the laser beams intersecting at a hohlraum entrance hole. This region is a key area in tuning laser light to achieve symmetric compression.



X-ray emission images from a NIF shot demonstrate how wavelength tuning transforms compression, changing the fuel capsule from a pancake shape to a sphere that is much more symmetric.

light on the wall near the capsule's two poles, and the inner cone shines light near the capsule's equator. (See *S&TR*, July/August 1999, pp. 4–11.)

Early results from the energetics shots indicated that the capsule was compressed into a pancake shape, rather than a uniformly round sphere. That is, less energy reached the equatorial regions of the pellet than the top and bottom, likely because light was scattering within the hohlraum. The inner cone needed more power to make up for scattering losses and avoid a pancake shape. Shifting the power balance of the two cones required changing the color, or wavelength, of beams forming the outer cone. Glenzer explains, "By changing the wavelengths of laser light, we can control where the light goes."

This new technique, called wavelength tuning, had been calculated a year earlier by Livermore physicist Pierre Michel. It uses the grating effect that occurs when the overlapping beams forming the inner and outer cones enter the hohlraum and interact with the plasma they create. Tuning these beams with respect to one another controls the power distribution in the hohlraum because the grating effect redirects light, just as a prism splits and redirects sunlight according to its wavelength.

With this technique, says Meezan, "The laser can deliver a lot more power to part of the hohlraum without having to increase production." In fact, it delivered at least 25 percent more power to the inner cone and effectively redistributed power after beams left the laser. This sort of precision tuning is possible because of NIF's flexibility and allows shot designers to make the most efficient use of the available beam energy.

Fusing It All Together

Glenzer and Meezan both note that an exciting aspect of the energetics shot series was bringing together so many aspects of ignition experiments for the first time. The shorter pulses and lower power levels on the OMEGA laser simply cannot match those of NIF. With NIF, researchers can study all the vital aspects of laser and target physics in the same experiment. "Even the wavelength tuning is enabled by NIF's scale," says Glenzer. He adds that combining NIF's long, plasma-producing pulses with larger hohlraum designs made this effect possible.

The NIC team continues to refine the hohlraum design and performance. To reach the peak radiation temperatures of 300 electronvolts, or more than 3 million kelvins, required for ignition, researchers must still pair a slightly larger hohlraum with somewhat higher energy levels. So far, shots have peaked at 285 electronvolts. NIC scientists must also prove that they can achieve the necessary symmetry to compress the fuel capsule by about double the amount achieved to date. Upcoming experiments will test ignition-sized hohlraums and target capsules filled with ignition fuel. Additional neutron diagnostics will be activated as well to examine the physical processes occurring inside the capsule.

Excitement and expectations continue to build throughout the fusion energy community worldwide as the NIC team releases results from the energetics shot series. The management team at the Laboratory's NIF and Photon Science Principal Directorate has seen a marked increase in applications from other research organizations proposing experiments at the Livermore facility. And the shot series has already inspired the first set of astrophysical experiments on NIF, using the hohlraum designed for the energetics sequence. Thanks to a team effort and spectacular results, NIC scientists are gaining confidence that they can meet the NIC challenge—producing the implosion conditions needed to drive ignition.

—Rose Hansen

Key Words: Brillouin scattering, cryogenics, energetics, fuel capsule, hohlraum, inertial confinement fusion, laser–plasma interaction, National Ignition Campaign (NIC), National Ignition Facility (NIF), Raman scattering, target design.

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